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Examining the Level of Service Consequence of Transit Signal Priority During Urban Evacuation

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Abstract

This research answers the question, during an urban evacuation should regional planners allow transit units signal priority when police assisted traffic controls are not an option. A case study of Washington D.C. shows allowing transit signal priority (TSP) during an urban evacuation has little to no effect on evacuation clearance time. Furthermore, four non-prioritized units are required to accomplish the task of three prioritized vehicles.

Keywords: Urban Evacuation; Transit Signal Priority; Microsimulation

1. Introduction

Customary practice for urban emergency evacuation is to situate police officers at intersections throughout the evacuation area. However, this is not always an option. When circumstances place officers in immediate danger, the officers are removed from the situation. In cases of major disaster where environmental factors such as the presence of fire, chemical plume, radioactive fallout (nuclear contaminated wind and dust) do not permit police presence, decision makers are forced to rely solely on automated traffic control measures. During the attack of 9/11, literally hundreds of first responders lost their lives when the World Trade Centers came crashing down (*National Commission on Terrorist Attacks Upon the United States, 2004*). Unlike the World Trade Centre, where the threat of disaster was unknown, intentionally exposing first responders to extremely hazardous conditions (where loss of life is not a possibility, but the ultimate logical conclusion) is not something that is practiced.

This dilemma is then compounded in high-density urban areas where transit is required to assist the egress of special needs population, car-less populations, and otherwise stranded populace. Transit vehicles, as in the form of buses, are in great demand. With only a finite number of available units, buses are required to make multiple trips in and out of evacuation zones. Therefore, it is within reason that some regional municipalities would allow transit priority to hasten trips made by buses. Minimizing bus travel time allows for more trips to be made optimizing the number of buses available. However, studies in the past have shown that during times of high roadway demand, transit priority causes major delays for vehicular traffic (*Dion and Rakha, 2005; Smith et al., 2005*). Priority may increase the number trips made by buses to special need areas, but this could have a devastating effect to the overall egress of the evacuation traffic.

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Therefore, there is a need to examine operational costs and benefits associated with evacuation policy which provides priority to transit vehicles during the evacuation process. The objective of this research is to test the effects transit signal priorities has for both transit vehicles and personal vehicles during a no-notice emergency evacuation within an urban area. To accomplish this, an evacuation of an urban downtown corridor is utilized as a case study.

2. Research background

Hurricane Katrina in 2005 had a devastating effect to the gulf coast region of the United States, namely New Orleans, La. In preparation of the storm, evacuation orders were given 48 hours in advance. Vehicular response to this was overwhelming, resulting in the majority of citizens evacuating without major issue. However, the lack of plans to evacuate people dependant upon transit resulted in hundreds of deaths that could have otherwise been avoided (*Schwartz and Litman, 2008*). (*Wolshon, 2002*) discusses the primary reason for noncompliance to evaluation orders is lack of reliable transportation. Had plans to use transit been successfully developed and implemented, the death toll from Hurricane Katrina would have been drastically decreased.

Since this incident, a series of publications by both public and private organizations highlight guidelines to assist in the evacuation effort utilizing public transit (*Balog et al., 2005; Federal Transit Administration, 2006; Litman, 2006; Congress on the Catastrophic Hurricane Evacuation Plan Evaluation, 2006; U.S. Government Accountability Office, 2006; Federal Transit Administration, 2007; The Role of Transit in Emergency Evacuation, 2008; Schwart and Litman, 2008*). (*Balog et al., 2005*) is a guide intended to support public transportation activities in order to improve the serviceability of local communities during a major disaster. It approaches the problem by incorporating local, state, and federal emergency planning agencies, as well as first responders and transit providers. (*6*) investigates the potential role transit can play in assisting with the evacuation and eventual re-entry of evacuees. (*Federal Transit Administration, 2006*) provides local transit agencies information on the best practices for providing disaster response and recover support to aid in relief efforts. (*Federal transit Administration, 2007*) reviews how state department of transportations, metropolitan planning organizations, and transit agencies are addressing the needs of populations which are more vulnerable to major catastrophic events. Provided by this publication are resources which may assist metropolitan areas incorporate the needs of evacuees with mobility concerns. (*Litman, 2006*) recommends a series of polices and best planning practices to ensure an efficient and equitable transportation system in the event of a major disaster by examining the short-comings of the Hurricane Katrina and Rita evacuations. (*Schwartz and Litman, 2008*) assists transportation professionals with the planning and coordination of transit operations during the emergency event. Recommendations are proposed that are intended to prevent confusion and inefficiency with proper planning and coordination practices. Prepared for the U.S. Congress by the U.S Department of Transportation in conjunction with the U.S. Department of Homeland Security (DHS) (*Congress on Catastrophic Hurricane Evacuation Plan Evaluation, 2006*) is a review and assessment of Federal and State emergency evacuation plans in response to major hurricanes in the gulf coast region. Within the findings are recommendations; emphasis is placed on the public transportation operations and disadvantaged populations. (*U.S. Government Accountability Office, 2006*) recommends that the DHS is accountable for the clarification of state and federal responsibilities with regard to providing transportation assistances to disadvantaged populations during an evacuation event.

In addition to reviewing polices and best practice procedures, researchers have used traffic modelling and traffic simulation tools to better replicate and understand the dynamics of emergency evacuation (*Southworth, 1991; Noh et al., 2009; Mastrogiannidou et al., 2009; Naghawi and Wolshon, 2010; Chen and Chou, 2009-17*). (*Southworth, 1991*) developed by the Oak Ridge National Laboratories is a comprehensive literature review of regional emergency evacuation modelling procedures. This research looks at the state-of-the-art in evacuation modelling for trip generation, trip departure curves, destination choice and route choice. (*Noh et al., 2009*) address similar concerns for evacuation modelling but differs in that this research develops models corresponding to no-notice urban evacuations. The models developed by (*Noh et al., 2009)* assume that evacuees must flee from their current position without a return trip home. These models use data which is typically collected by regional transportation planners.

The modelling tools and procedures developed in past studies have been used in numerous evacuation simulation papers published in peer-reviewed journals (*Southworth, 1991; Noh et al., 2009*). These models are applied to simulation environments to solve a variety of evacuation problems. The focus of this research is transit-based evacuation simulation models as seen (*Mastrogiannidou et al., 2009; Naghawi and Wolshon, 2010; Chen and Chou, 2009*). (*Mastrogiannidou et al., 2009*) examines the issues associated with transit-assisted emergency evacuation procedures in highly populated urban areas. It approaches the problem by developing a transit-based emergency evacuation model and integrating it with a current state-of-the-art micro-simulator within a dynamic route choice environment. (*Naghawi and Wolshon, 2010*) again integrates transit-based and traditional auto-based evacuation strategies within a single-simulation environment. This paper examines the advantages of alternative transit routing schemes in order to increase the performance of the current evacuation procedures. (*Chen and Chou, 2009*) approaches the problem of transit-assisted evacuation as a bi-level optimization model to determine transit-evacuee pick up and drop off locations. Furthermore, this research examines the effects that contra-flow strategies have on transit-assisted evacuations.

3. Methodology

The methodology of this research is partitioned into two components: the development of the evacuation simulation environment and transit operations and signal priority. Figure 1: Flowchart of methodology illustrates how these two components merge within the simulation. Street geometry, signal timing data, traffic counts and transit information (schedule, stop location, dwell time, etc.) are fed into the transit signal priority logic and the simulation platform. Socio-economic data, census data and regional evacuation data are passed into the emergency evacuation trip generation and trip distribution models. From these models, an evacuation origin-destination (O-D) matrix is generated. This matrix is then used in the simulation platform to create a realistic emergency evacuation traffic model. From this simulation model, measures of effectiveness (MOE's) such as travel time, evacuation clearance time, delay time etc. are calculated. These MOE's are then extracted from the simulation platform, assumptions are checked, conclusions made and recommendations brought forward.

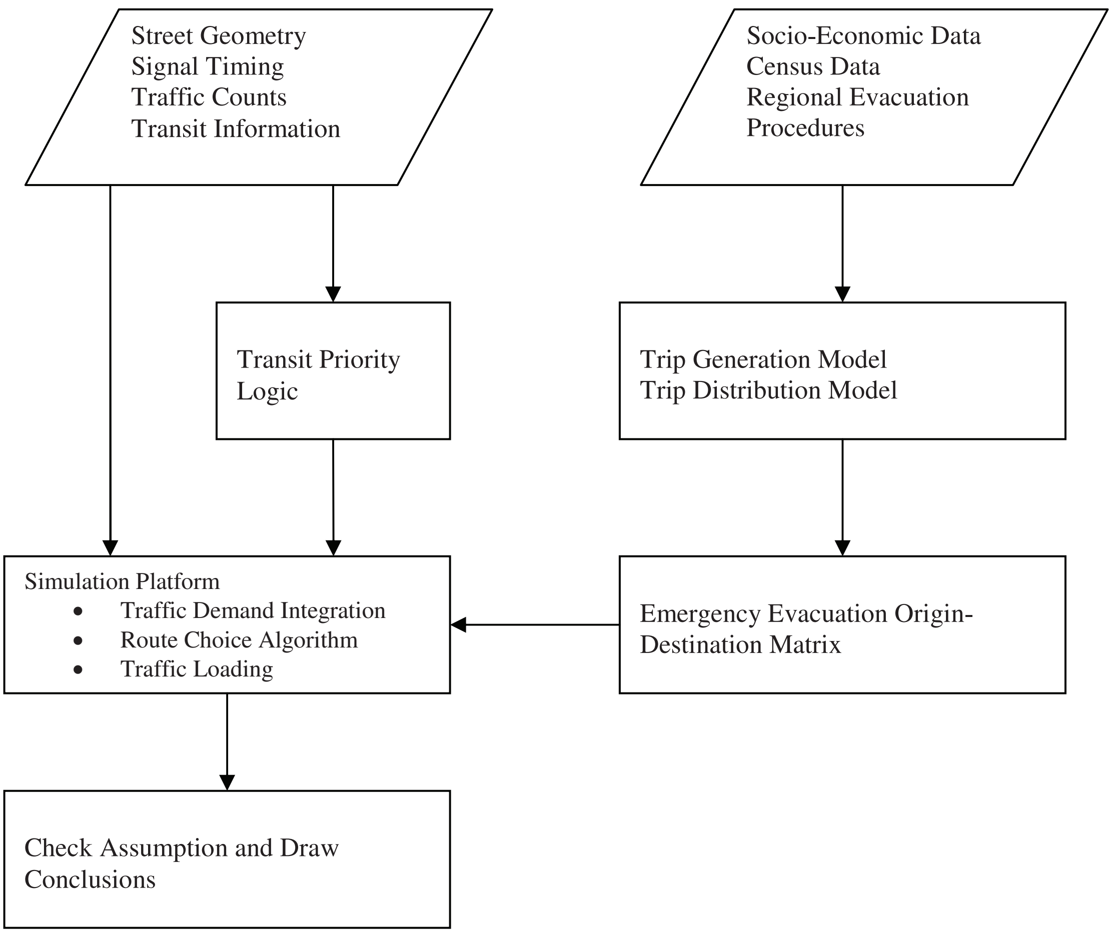

Figure 1: Flowchart of methodology

3.1 Evacuation modeling

The evacuation supply and demand modelling, in the form of trip generation and trip distribution, are adopted from (*Southworth, 1991*) and (*Noh et al., 2009*), respectively. Alterations to these formulations, as they pertain to the case study, are minor (*Parr, 2010*). From these two models, the evacuation O-D matrix is created. This O-D matrix is then merged with the background demand to form a seamless cohesion between the two road network users. The background demand and signal-timing plans were provided by the DDOT, as they pertain to the case study. Mode choices are reduced to personal vehicles and transit. It is assumed that all other modes have marginal impact on the traffic network and represent an insignificant reduction in travel demand. Route choice is modelled using a variation of Dijkstra's label setting shortest path algorithm (*Transportation Simulation Systems, 2008*).

3.2 Transit operations and signal priority

Transit operations within the simulation environment are designed to mimic reality. Transit buses adhere to schedules, make stops, and interact with traffic. For this paper, the transit operations are identical to the case study. The transit signal priority however, is developed independently of the transit operations due to the fact that the case study does not currently allow transit priority at intersections. The transit signal priority logic is designed with two goals in mind. The first of which is to match the results seen in the field; the logic must decrease transit travel time between 9-35% and must have only a marginal effect on personal vehicles (less than 5% increase in travel time) during the weekday peak periods (*Smith et al., 2005*). These values represent a comprehensive review of a variety of transit signal priority logics used in North America as researched by Smith et al., 2005. The second objective of the logic, it must have a seamless interaction with the traffic simulation environment. The logic must be diverse; so it may be programmed into the simulation. Figure 2: Signal priority logic visually displays the logic in flowchart format.

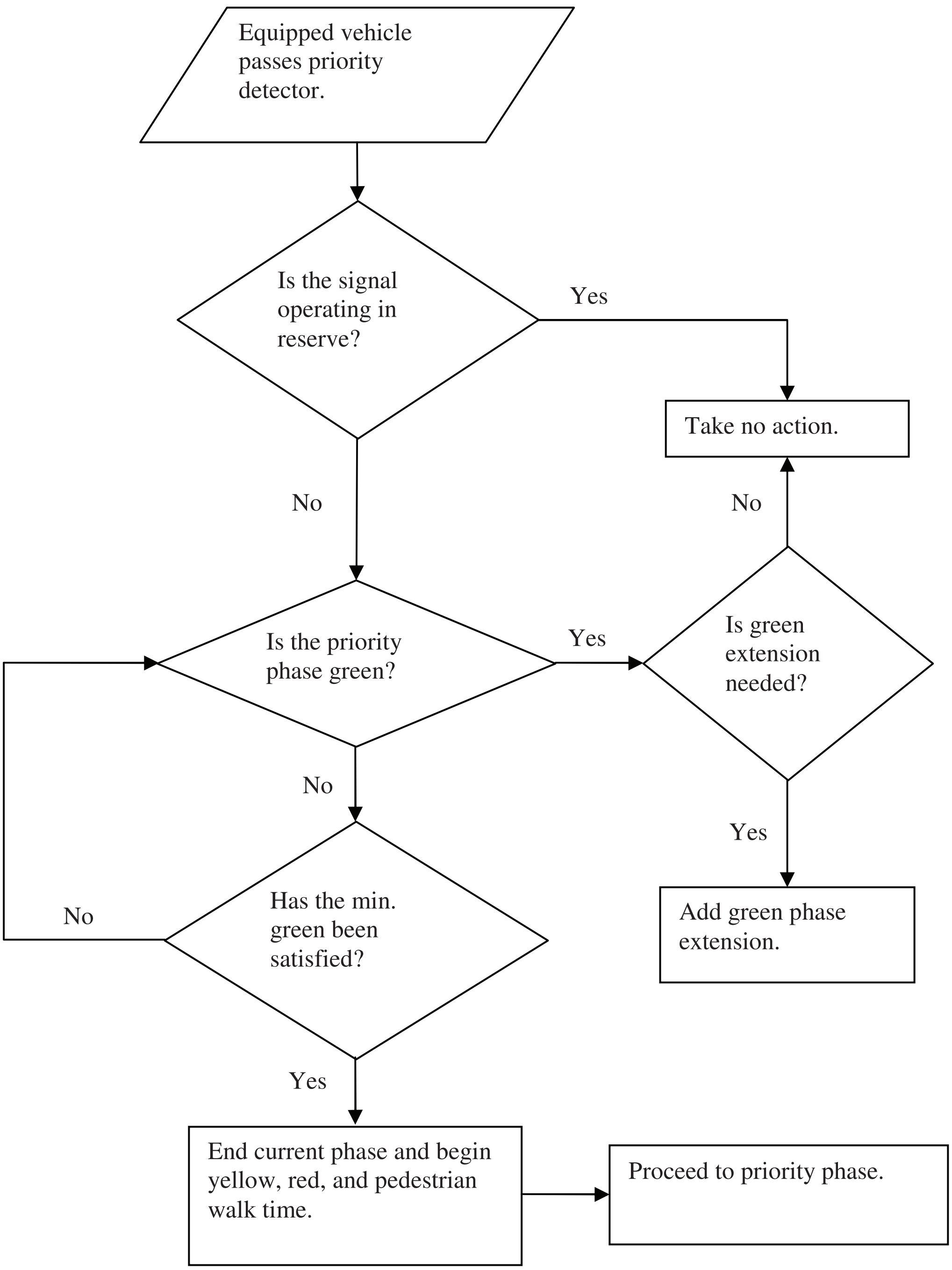

Figure 2: Signal priority logic

This logic is a generalized early-green with red-truncation signal priority representing the "typical" state-of-practice and fairly common. An equipped vehicle is one, which is capable of communicating with priority-enabled traffic control devices. As this vehicle passes a priority detector, the priority request generator is activated; simply put the vehicle "checks in" to the intersection. Predefined into the traffic controller, the priority request server knows the location (distance upstream from the intersection) and the route of the vehicle. The first question the priority request server must answer is, "Is the signal operating in reserve?" Reserve is defined as the time that priority is not available. From the practices observed in the literature review, this duration is set to one cycle length.

If the signal is operating in reserve, no action is to be taken. When the signal is not in reserve, the next question to be asked by the priority request servers is, "Is the priority phase green?" Is the phase being requested, the same as the phase currently being served? In this case, the server must know if a green extension is needed. Is the vehicle predicted (based on detector distance and travel speed) to pass the stop-line (check out) before the onset of the yellow time? In cases where the vehicle is predicted to "check out" in time, no action is taken. When the priority request server predicts the end of the cycle, it restarts the priority green phase. If the vehicle approaching arrives when the priority phase is not green, the priority request server must know whether the current phase has completed its required minimum green time. The minimum green time is the predefined green time a phase is required to receive, regardless of the priority request. Once again, from the literature review, this logic uses duration of 10% the cycle length. If this is the case and the minimum green has not been satisfied, the request is delayed until such time. Once the minimum green has been satisfied, or in the case, a priority request is generated after the minimum green, the priority request server proceeds with the request. This is done by ending the current phase, advancing to the yellow, all-red and walk time, then immediately proceeding to the requested phase. Once the vehicle has passed the stop-line detector, it "checks out" and enables the reserve time.

4. Case study

The study area is a 14-intersection corridor located in the Southeast corner of Central DC; NW 7th Street from SW E Street (South) to NW Pennsylvania Ave, West to NW 12 Street (Figure 3: Study corridor). This area is located just a few blocks west of the capital building. The area's selection results from the location with regard to the major metro stations within the city. Moreover, this corridor plays a crucial role in the city's evacuation plans.

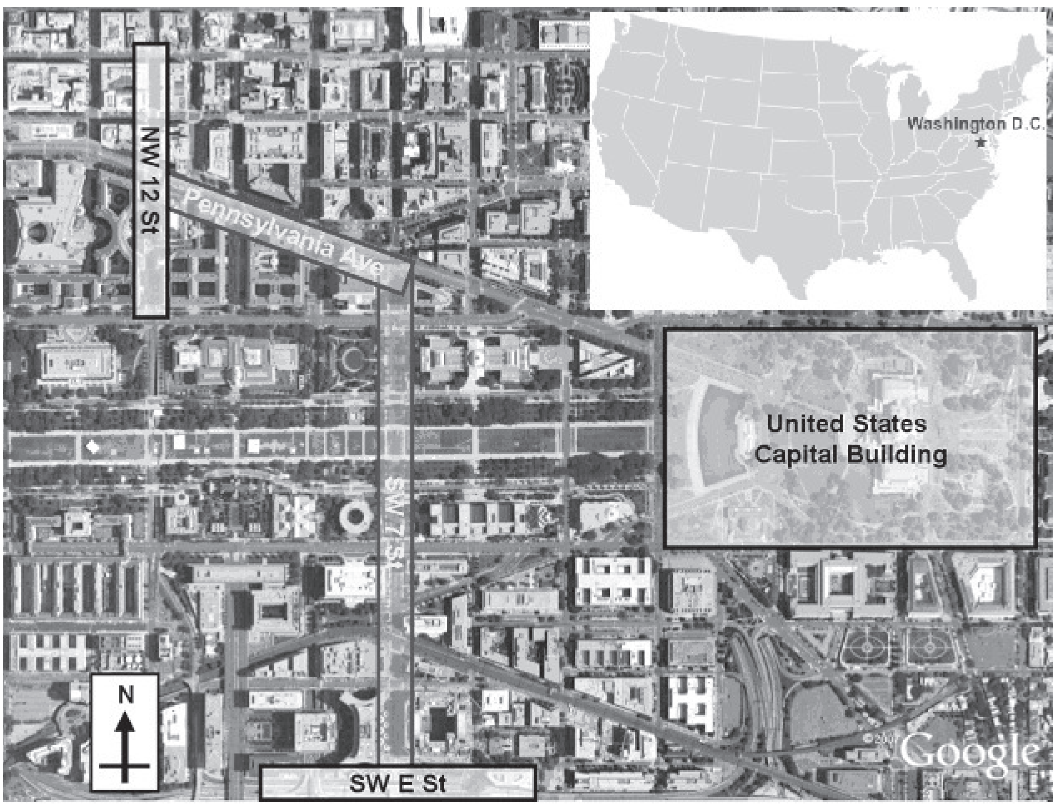

Figure 3: Study corridor

The current evacuation plan for Washington DC is defined in the District Response Plan: Emergency Transportation Annex (ETA) (DDOT, 2006). Developed in 2006, the ETA presents the plans, organizations, structures, and procedures used in the event of a disaster resulting in need for a regional evacuation. This plans call for the use of 19 major corridors to assist in the evacuation process. These corridors are the primary evacuation routes and are all major arterials that span from Central DC to the I-495 beltway. Within the study area Georgia Ave (NW 7 St) and NW Pennsylvania Ave are two of the major corridors for evacuation.

Within the borders of the case study exists 34 bus lines. For the purpose of this paper, some bus lines were excluded from being modelled in the network. Selection of lines among these 34 possibilities was based on two criteria: each line must involve a thru or left turn movement and each line must use more than one intersection within the study corridor. Buses that do not require priority (right hand turns only) or buses who simply pass through the corridor and do not traverse it, are excluded. Based on this, 17 lines were removed from consideration, leaving 17 lines to be modelled.

Each of the 17 bus routes are coded into the simulation network. Bus stop locations are mapped using GIS files (*DC GIS Data Clearinghouse, 2008*). Mean bus stop duration and standard deviation were manually coded. These values are 12.29 seconds and 13.47 seconds respectively, as previously researched (*Dueker et al., 2004*). Bus departures, time at which the bus arrived into the network, are found using a trial and error method. Testing and modifying bus departure times, bus stop arrivals are coded on schedule. Within the network, bus departure times for each bus operation (roughly 300 individual bus departures) were manually coded starting at 4:00:00PM until 10:00:00PM ensuring all operations throughout the entire study period are captured. From the 17 lines within the network; two are selected to be evacuation bus routes, the 901 and 905. These routes are selected for their location and serviceability. These two lines navigate the entire length of the corridor, northbound entering from SW 7 St and exiting westbound NW Pennsylvania Ave and vice-versa for southbound trips.

The ETA states all transit operations during an emergency are to be put under the control of the Washington Metropolitan Area Transit Authority (WMATA). All transit services (both rail and bus) are directed to maintain normal operating procedures, schedules and routes so long as they are not directed otherwise. In the event an emergency requires additional resources (buses), an incident commander will notify WMATA for assistance. In the case that operations of rail lines need to be stopped, additional surface transportation will fill the transportation mode gap until such time as rail service can resume operations. Furthermore, all intersections will operate on PM peak hour signal-timing plans unless otherwise specified.

4.1 Simulation environment

The Washington DC road traffic network is developed using the microscopic traffic simulation software platform Aimsun NG Professional 6.0.5. This model encompasses the study area on SW 7 St from SW E St to NW Pennsylvania Ave and west on NW Pennsylvania Ave until NW 12 St. Within the model, exist fourteen intersections and eighty-three street segments totaling five miles in length with 14 miles in lane length. The streets intersecting the primary corridor (all street that are not SW 7 St or NW Pennsylvania Ave) are terminated at the stop line of the upstream intersection. These street segments are modeled in AIMSUN NG 6.0.5 to match detailed GIS shape files and longitude and latitude match satellite photographs received from DDOT via personal request. The geometric features observed from these files where than compared with field observations to check their validity. Upon comparison these features (number of lanes, turn pockets, crosswalks, etc.) match the satellite images accurately.

Signal timing data for this research is provided by the DDOT. To acquire this data a personal request is made, in this case, by the Transportation Research Laboratory at Florida Atlantic University. The DDOT obliged and sent signal-timing plans divided into schedules, AM Peak, PM Peak and Midday off Peak hours. This information was delivered in the form of Synchro 7 optimization software files. Synchro has the ability of providing advanced coordination between traffic-control devices at separate intersections. This form of information dissemination is common in the traffic-engineering field. The traffic-control information from these files was copied directly into the simulation environment.

In addition to the signal timing data, the Synchro 7 files provide traffic count and street flow information collected and developed by the DDOT. This count information, collected in 2006 is used by the DDOT for its four-step modeling process. From this process, the DDOT develops traffic flow information for individual links. Therefore, using this count and flow information to develop traffic flow for background demand for this research is an accurate assumption. By utilizing this information, trip generation, trip distribution, mode choice and route choice models do not need to be developed specifically for this study. The result of these model, previous developed by the DDOT are used instead.

4.2 Calibration

Floating car travel time runs were conducted on two corridors within the study region during the PM peak hour: North, from the intersection of SW 7 St and SW D St to NW 12 St and NW G St, utilizing SW 7 St to NW Pennsylvania Ave. And South, from the intersection for NW 11 St and NW E St to SW 7 St and SW D St, via NW Pennsylvania Ave to SW 7 St. These trials were conducted for each corridor, from 4:00 pm to 6:00 pm. From these trials, travel time data was collected and used to calibrate the network. To visualize discrepancies, a series of time-space diagrams were created. Figure 4: Calibration time-space diagram is an example of one such diagram. After the analysis was complete, it was impossible to statistically distinguish the field-observed travel times and the simulated travel times within a 95% confidence level.

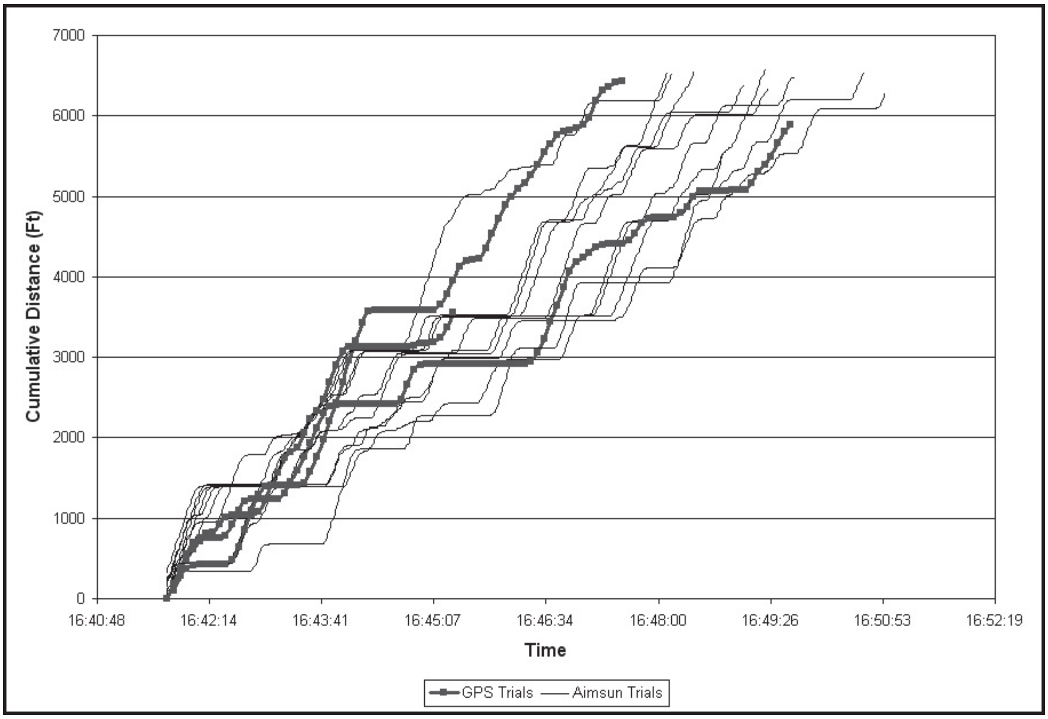

Figure 4: Calibration time-space diagram

4.3 Evacuation scenario

The evacuation scenario is a dirty bomb terror attack at L'enfant Plaza metro station (Figure 5: Emergency evacuation scenario outlined by a small dark circle located to the south). A dirty bomb is any explosive device that is surrounded by radioactive material. L'enfant Plaza metro station connects four metro lines (blue, green, yellow, and orange) making it a crucial interchange for commuters. A dirty bomb attack at this station could immediately kill hundreds while simultaneously disrupting the primary means of evacuating the radiological fallout. The evacuation from such an attack would be vital. Longer evacuation times resulting in the commuter disturbance at the metro station will leave citizens exposed to the fallout longer, and thus more likely to suffer the effects (*U.S. Nuclear Regulatory Commission, 2007*). The lasting consequences would be devastating; rendering a portion of Washington DC contaminated with fallout.

It was assumed that the attack would take place around 5 PM, just about the time when most of the employees leave their offices and try to get on the subway. This timing is ideal for the terrorists; commuters will be arriving at the metro station, increasing the casualties of the immediate explosion. The nearby traffic, already accumulating as a result of the time of day, is then saturated by evacuation traffic; causing gridlock and exposing people to fallout for longer periods of time increasing the chances of serious injury or death.

Once decision-makers have become aware the region is being attacked by a nuclear device (17:00), the order to evacuate the immediate area (a half-mile radius around L'enfant Plaza) is given. Evacuees are directed to safe-zones via radio and loudspeaker, where they are examined and treated for radioactive exposure. Evacuees are directed away from the blast zone, where high concentrations of radioactivity are found. As a result, only half of the evacuation circle contributes to the study corridor located north of the blast site. Figure 5: Emergency evacuation scenario displays this in a lightly shaded semicircle. Because of the contaminated air and dust encompassing the region, police are directed to stay away from the area until hazardous material (hazmat) teams can provide them with the protective equipment (hazmat suits) needed. Any on-hand equipment is assumed to be used by medical personnel treating and transporting evacuees. This lack of vital resources means the evacuation will have to take place without police assistance at intersections. The entire region is evacuated using the signal-timing plans specified in the ETA, the PM peak hour (DDOT, 2006).

Three safe-zones are chosen; The International Convention Center to the north, The Ronald Reagan Trade Center to the west, and I-395 northbound to the east; where evacuees can seek assistance at other facilities further away. These safe-zones are delineated by shaded boxes with dark outline in Figure 5: Emergency evacuation scenario. By 17:20, thirty minutes after the explosion, it is assumed that police have arrived outside of the contaminated area and have closed all roads leading into this region. No additional background traffic will enter the study area from this point on. Meanwhile, the incident commander has called for additional resources (buses) to assist with the evacuation of non-critical victims (walking wounded) at the explosion site. The evacuation of this population is vital; therefore any on-hand hazmat suits will be used by medical staff running the evacuation buses. The number and arrival time of these buses is unknown and therefore is modelled using headways. Because the transit signal priority logic is dependent upon headway, a variety of headway scenarios must be tested. These test scenario headways vary (20 minutes, 15 minutes, 10 minutes, 5 minutes, and 2 minutes) in order to cover a wide range of realistic outcomes. All other routes remain on their normal schedules, as long as they do not pass through the evacuation area. The only buses which operate within the fallout region are the 901 and 905, which are driven by hazmat-equipped medical personnel and operate on the specified headways.

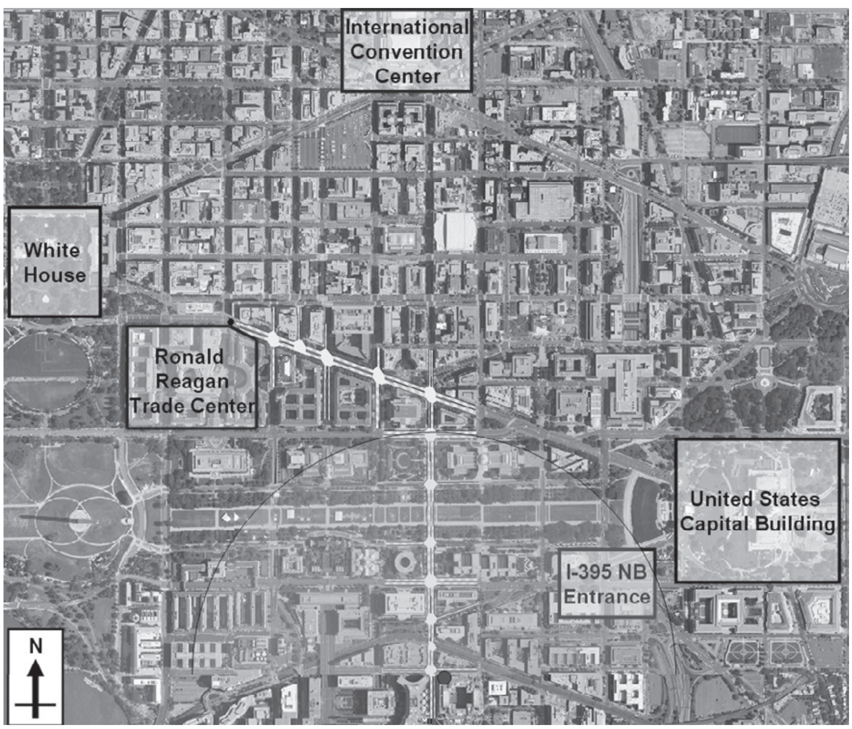

Figure 5: Emergency evacuation scenario

Figure 5: Emergency evacuation scenario depicts the study area. Major landmarks and safe-zones are outlined for reference. The corridor is animated, with the traffic simulation overlay. The explosion site is shown as a small dark circle at the south of the figure, with the network-contributing evacuation semicircle lightly shaded around it.

5. Results

Using the simulation environment developed for the case study, fifteen scenarios are tested (5 varying headways with 3 priority strategies). For the accuracy of the results, each of the fifteen scenarios are simulated ten times and the results averaged, constituting one-hundred and fifty individual simulations runs, totalling approximately twenty-four hours of non-stop data compiling. The three signal-timing plans tested are: Priority, Select Priority, and No Priority. The Priority scenario gives signal priority to all buses. Select Priority only gives priority to evacuation bus routes (line 901 and 905) and No Priority does not allow any transit signal priority.

Each scenario is looked at from the perspective of three different stakeholders: the transit evacuee not located at the site of the disaster (bus riders not using lines 901 or 905), the transit evacuee located at the disaster site (riders of lines 901 and 905) and the evacuee using a personal vehicle. For future reference, these stakeholders are noted as; All Bus Routes, Select Bus Routes and Personal Vehicle, respectively. Each of these stakeholders has something to lose or gain by incorporating one of the three priority strategies being tested.

Clearance time is the time or duration which is required for the complete evacuation of a region. This time begins once the evacuation order is given and ends once all evacuating traffic exits the network. This time represents how long evacuees are exposed to risk as a direct result of the transportation system and therefore constitutes the most meaningful MOE in evacuation traffic studies. Table 1: Evacuation clearance time displays the clearance time of each strategy for the given headway used for northbound 901 and 905 routes. The clearance time for this table is the first ten-minute internal during which no vehicles exit the network. This value ranges between 9:40:00 PM and 10:00:00 PM or four hours and forty minutes to five hours after the evacuation order is given. The slightness of this range is a testament to the consistency of the simulation model. Regardless of the priority control plan used, the evacuation clearance time remains relatively unaffected. From this table, faintly lower clearance times are observed for the No Priority strategy, followed by Select Priority, and finally Priority. Based on the evacuation clearance time, no definitive evidence is shown that would suggest any hindrance caused by the priority strategies.

Table 1: Evacuation clearance time

Clearance Time	**Evacuaton Route Headway**				
Control Plan:	**20 Min**	**15 Min**	**10 Min**	**5 Min**	**2 Min**
No Priority	9:40 PM (4:40)	9:40 PM (4:40)	9:40 PM (4:40)	9:40 PM (4:40)	9:50 PM (4:50)
Priority	10:00 PM (5:00)	9:50 PM (4:50)	9:50 PM (4:50)	10:00 PM (5:00)	10:00 PM (5:00)
Select Priority	9:50 PM (4:50)	9:40 PM (4:40)	9:50 PM (4:50)	9:50 PM (4:50)	9:40 PM (4:40)

Figure 6: Travel time for all bus routes with 5 minute headway illustrates the average travel time witnessed by the All Bus Route stakeholder when a five-minute headway is used for lines 901 and 905. This figure shows the benefits of transit priority during an evacuation. Without the priority, a significant portion of buses are stranded on side streets; prevented from continuing on their routes. These buses experienced, during some instances, travel times nearing 1,400 seconds (twenty-three minutes) per mile. Delays of this magnitude can leave transit-dependent populations stranded, with no other mode of transportation to deliver them from pending death. When the priority logic is used, traffic signals are forced to service side streets, eventually alleviating the congestion that was preventing the passage of the transit vehicle, resulting in an approximate 25% reduction in transit travel time. This pattern is consistent during all 150 simulated evacuation trials.

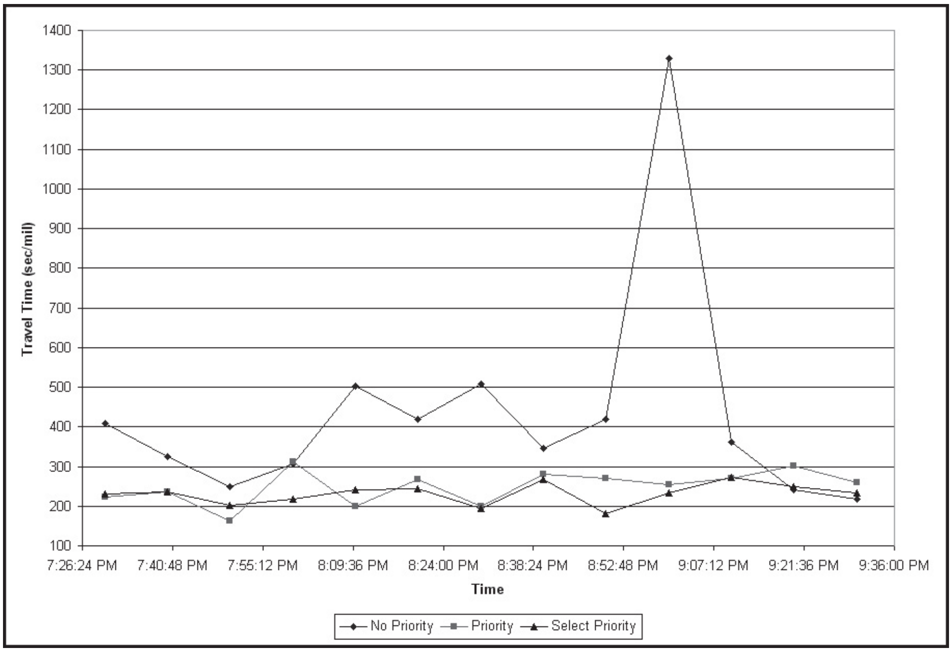

Figure 6: Travel time for all bus routes with 5 minute headway

6. Conclusion

In conclusion, transit signal priority during the evacuation of an urban area is shown to have little to no interference with evacuation clearance time. Even in the case where bus headway is set to two minutes or an "as soon as possible" approach, non-transit evacuees experience no significant changes in clearance times when transit signal priority is granted to all b. Furthermore, by allowing transit vehicles priority during the evacuation a level of service increase is experienced by transit evacuees corresponding to a 26% reduction in travel time. This signifies that four non-prioritized units are required to accomplish the task of three prioritized vehicles. This savings is then translated into additional trips being made by transit units. More trips means shorter evacuation times, smaller delays in treatment for injured populations, and ultimately fewer deaths caused by a disaster.

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